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Characterizing Finger Pitch and Roll Orientation During Atomic Touch Actions

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ABSTRACT

Atomic interactions in touch interfaces, like tap, drag, and flick, are well understood in terms of interaction design, but less is known about their physical performance characteristics. We carried out a study to gather baseline data about finger pitch and roll orientation during atomic touch input actions. Our results show differences in orientation and range for different fingers, hands, and actions, and we analyse the effect of tablet angle. Our data provides designers and researchers with a new resource to better understand what interactions are possible in different settings (*e.g.* when using the left or right hand), to design novel interaction techniques that use orientation as input (*e.g.* using finger tilt as an implicit mode), and to determine whether new sensing techniques are feasible (*e.g.* using fingerprints for identifying specific finger touches).

Author Keywords

Human factors, finger orientation, touch surface.

ACM Classification Keywords

H.5.2 Information interfaces (*e.g.* HCI): User interfaces

INTRODUCTION

Touch interfaces have a specific set of interactions, including tap, hold, drag, or flick, using one or multiple fingers. The capabilities and characteristics of these interactions are well known from the system’s perspective (*e.g.* what they can be used to accomplish in an interface), but less is known about how they are carried out by users. There can be substantial variability on the user’s side of the screen – for example, there are many potential ways in which a person could execute a tap, a hold, a drag, or a flick (with different fingers, or with the hand held in different postures) – and although all of these may appear identical to the touch device, there can be differences for the user.

There are several reasons why it is important for designers to understand the constraints and characteristics of the human side of touch input. This information can be used to better understand what is possible with touch - for example,

certain kinds of interaction may be difficult to achieve with certain fingers, or with the non-dominant hand, or in constrained physical settings; and it may be possible to reduce error or fatigue by encouraging particular postures and orientations. Second, although touch devices currently have limited ability to sense the user’s hand above the surface, these capabilities may soon be common [37], and if information about the touching hand can be sensed, it presents new design possibilities for enriching the input signal: fingers could be held at different angles to engage different implicit modes, and systems could filter touch input to reduce errors caused by inadvertent touches (*e.g.* a touch with a finger orientation that is well outside the normal range could be classified as accidental). Third, information about the hand can inform designers about whether certain advanced techniques are possible - for example, information about how people touch the screen can determine whether fingerprint identification is feasible (based on whether the pad of the fingertip contacts the screen), or whether fingers can be identified from their orientations alone.

An obvious first step in exploring these issues is to determine what users actually do with their hands and fingers in current interactions with touch devices. A baseline study can indicate whether there are meaningful differences in posture for different fingers, different hands, and different tasks, can determine whether some advanced interactions such as fingerprint identification are possible, and can indicate mean angles and ranges for designers who want to develop new interaction techniques using finger orientation as input. To provide this baseline information, we developed tools to test and analyse finger orientation, and carried out a study where we recorded orientation data as people performed atomic touch actions (single-finger taps, holds, swipes, and drags; and two-finger pinches and rotation gestures).

The results from our study provide both baseline information and new insights about the user’s fingers above the touch screen:

- the little, ring and middle fingers of a given hand have similar pitch and roll orientations while interacting, whereas the thumb uses a complete different range.
- differences between fingers are mainly due to the difference of roll angles.
- a given finger uses different orientations as a function of the number of contacts involved in a gesture.
- there are substantial effects of tablet angle on touch orientations.

Our data also provides us with new information about the design opportunities mentioned above:

- the relatively low pitch angles used during one-finger interactions means that it should be possible to use high pitch angles as an extra degree of freedom
- the thumb can be differentiated within the fingers of the same hand using orientation alone.
- finger identification could be enabled by fingerprint recognition if the side of the finger pad provides enough information for discrimination.

Our work makes three main contributions. First, we provide a low-cost methodology for tracking and analysing unconstrained natural finger orientation on the touch surface. Second, we provide a set of baseline results about orientation in tasks and conditions with good ecological validity for all the fingers of both hands for one setting (a flat tablet in front of the user), and additional analyses about how changing the angle of the tablet changed people’s finger orientations. It helps define the ranges of used and unused orientation angles for each finger in a variety of tasks and provide insights to designers when developing interaction techniques that leverage finger orientation without interfering or changing current habits. This baseline data is made available to other researchers who wish to do further research¹. Third, we provide initial explorations of several use cases that show how finger orientation information could be used to enhance interaction with future generations of touch devices.

RELATED WORK

When it comes to understand the human factor, there are at least two possible approaches. The most common one consists in studying user performance adopting the system perspective. Those studies, such as Fitts’ experiments [5], allow researchers to investigate the influence of factors by examining the inputs received by a system (*e.g.* measuring time, error rates or accuracy). A second approach consists in adopting the user point of view by observing how we respond to a system, but also characterizing how we interact with it. In this paper we use the latter and observe how we physically use a touchscreen.

Angles

The angles used to describe the orientation of a finger are those typically used to describe airplane orientation (figure 1): the yaw (*i.e.* angle around the vertical axis); the pitch (*i.e.* angle around the lateral axis); and the roll (*i.e.* angle around the longitudinal axis). The yaw describes the direction at which the tip of the finger points (*e.g.* in a room, which wall the finger is pointing at). The pitch describes the altitude at which the tip of the finger points (*e.g.* in a room, is the finger pointing to the floor or the ceiling). The roll angle describes the direction that the palm of the hand faces (*e.g.* in a room, is the palm facing the floor or the ceiling).

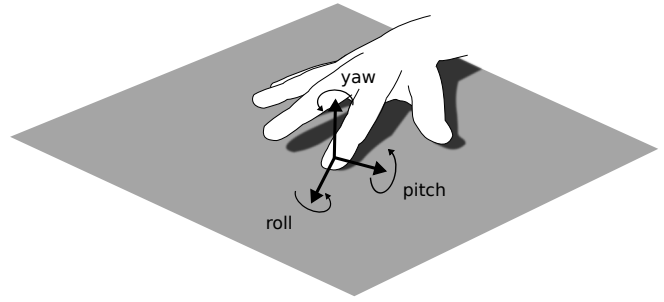


Figure 1: Angles (yaw, pitch and roll) describing a finger orientation.

Studying behavior

Knowing how people naturally interact with a system is insightful. It can guide the design of future devices in terms of ergonomics but also can lead to new degrees of freedom that can be leveraged for more expressive interactions.

Jacquier-Bret *et al.* observed users postures while carrying out their work on touch devices [15]. These researchers analysed which part of the body were used while executing common tasks and found that people’s typical usage may increase the risk of developing musculoskeletal disorders. Their observations led them to recommend considering human motion in the development of future touch screen devices as well as exploiting their findings to better adapt the interfaces to the users capabilities. Genaro *et al.* studied the wrist movements of older users interacting with touch devices using a motion capture system. Using their observations, they discuss the accessibility of interactive technologies, and also encourage designers to consider the ergonomic factor to ease the adoption of touchscreens by older users [24]. Bachynskyi *et al.* recorded users’ postures while interacting with different types of touchscreens [2]. Among other investigations, they looked at muscle activation and released a corpus to help researchers understand how we physically interact with touchscreens.

Concerning finger orientation, Mayer *et al.* controlled the yaw and pitch angles using 3D printed stands to evaluate the feasibility and comfort of touch input for stationary devices [21]. After compiling feasibility scores, they found that the non-comfortable yaw orientation zone covers 225° out of 360° , low pitch angles are preferred when in the comfort zone while high pitch angles preferred when in the non-comfort zone. From their observations, they derived guidelines to enrich interactions. For instance, finger pitch could be used as a new input to activate contextual features (*e.g.* contextual menus) and close to non-comfortable orientation ranges to activate critical features (*e.g.* reset to factory settings). Hoggan *et al.* realized a similar study controlling for 2 finger rotation gestures [12]. They concluded that contralateral anti-clockwise and ipsilateral clockwise rotations are prone to more ergonomic failures.

Knowing the actual range of orientations that we use could refine Mayer *et al.*’s design guidelines by identifying angles that are both not yet used and also feasible. The latter could then be leveraged to enrich the touch modality.

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Comparing fingers

Although performance studies, which rely on analyzing system inputs, are primarily used to evaluate the influence of design choices (such as comparing techniques [18, 10] or comparing instances of a technique [9]), they are also a great tool to study real world factors (such as touchscreen orientations [26], encumbrance [25] or grasps [29]). With the rise of interaction techniques leveraging finger identification [20, 32, 8], another external factor starts to become important: our own ten fingers.

Fingers have already been compared for different tasks. McManus *et al.* compared the fingers through the approach of motor control by measuring the *inter-tap interval* (the time between two consecutive finger taps) for all fingers [23]. Colley *et al.* [3] and Goguey *et al.* [7] compared their performance as well as users' preferences in Fitts' tasks. Roy *et al.* also looked at their reaction times and error rates [28]. Finally, Wang *et al.* evaluated the precision of different fingers in a tapping task [34].

Finger orientation

Previous works have mainly focused on sensing yaw and pitch finger orientation on touch surfaces to enhance interaction techniques. Wang *et al.* [33] estimated the yaw angle of a finger based on the shape of the contact captured by a vision-based tabletop. For static poses, the error around the yaw estimation varies between -5° and 6° (3° on average). For dynamic poses, the error around the yaw estimation varies between -27° and 30° (14° on average). In [27], Rogers *et al.* have a similar approach by estimating the pitch and the yaw angles from touchscreen capacitive images. They used the inferred pitch and yaw orientations to improve touch accuracy when acquiring targets. However they did not report figures comparing real finger orientations to the inferred ones. This was further exploited by Xiao *et al.* in [37] which not only estimated the pitch and yaw angles but also the roll angle. However, it is unclear to what extent the roll angle can be detected; this research demonstrated the use of the roll information with finger orthogonal to the screen or starting sideways and flat on the screen. For static poses, the error around the pitch estimation on a phone is 11° on average. Dang *et al.* also use the shape of the contact to detect the yaw and pitch angles [4]. They process the contours of the contacts from the infra red based table top image. Their algorithm yields a 75% recognition rate with a tolerance of less than 5° and 95% for a tolerance of less than 10° . Watanabe *et al.* estimate the force applied by a finger while contacting the screen as well as the pitch and yaw angles using a camera monitoring the light intensity emitted by the fingernail [36]. Their setup imposes a cumbersome camera mounted on the finger tip which constrains the natural finger orientation. Kratz *et al.* developed an algorithm capable of extracting the yaw and pitch angles by fitting a cylindrical model of the finger into a point cloud provided by a depth camera [16]. However, they acknowledge that a more complex finger model (for instance using joints) could be used to strengthen the detection. With the cylindrical model, a good orientation estimation implies a close-to-straight finger without others interfering. They reported the stability and performance of their system but no ac-

curacy measurement of the orientation was reported although they acknowledge being able to compute it using a motion capture system. Mayer *et al.* later used this method in [22] and found a potential offset of 13.1% on the pitch angle which can only range from 0° to 90° .

Using a vision-based system above a table, Zhang *et al.* estimate the yaw orientation of interacting fingers and use it to identify users in function of their position around the table top [38]. They reported the user recognition rate using their system but no accuracy measurement of the orientation was reported. Gil *et al.* leveraged the fact that different finger orientation yield different capacitive images [6]. They use those orientation to identify different finger on a smart-watch. However they impose a highly rolled thumb, a flat index and rolled middle finger. While the orientation is fair to assume for thumb, given the hand joints, and the index, the middle finger might not be used in a natural manner. They reported the finger recognition rates but not on the orientation retrieved.

Finally, Holz *et al.* introduced the use of fingerprints to increase the accuracy of touch interaction [13]. By analysing the portion of the user's fingerprint in contact and comparing it to a database of fingerprint examples, their prototype could infer the yaw, pitch and roll angles. However, even though this technological solution is promising, the recognition rate of the angles was not reported.

As measuring finger orientation is complicated, most prior work uses an approximation of the yaw and pitch angles, constrains the finger orientation, or assumes clean postures. To our knowledge, the natural pitch and roll orientations of fingers during typical touch interactions has not been investigated before.

EXPERIMENT

We conducted a within-subject design controlled experiment, to record pitch and roll angles of the 10 fingers while interacting on a touch screen.

Apparatus

To log the orientation of the fingers, we used a $0.5'' \times 0.7''$ IMU sensor² attached above the first phalanx using *Blu Tack* to avoid covering the pad of the fingertip and potentially changing participants' behavior while interacting (figure 2). The IMU was connected to an Arduino Leonardo³ plugged into a 2013 Nexus 7-inch Android tablet with a resolution of 1920×1200 pixels. A custom made Android application ran the experiment and logged the touch events as well as the orientation reported by the IMU at 50 Hz. The tablet was fixed using a tripod at a flat orientation. Users sat on an adjustable height chair. The height was set so that the tablet was within arms reach just above the lap level.

In this paper, we thoroughly describe pitch and roll finger orientations in the screen frame of reference for all ten fingers

²Ultimate sensor fusion (\$35.95): tindie.com/products/onehorse/ultimate-sensor-fusion-solution/

³Board available at \$19.80: store.arduino.cc/usa/arduino-leonardo-with-headers

when interacting with a flat surface. With our setup, such characterization for a non flat tablet is not possible. This state-of-the-art IMU provides reliable pitch and roll orientation in the world frame of reference, and therefore in the screen plane, using an embedded sensor fusion algorithm. However, given the nature of the movements (*i.e.* quick and non stable orientation over time) and the context of use (*i.e.* hardware in the vicinity), the relative inaccuracy of the yaw angle provided by the sensor prevents transforming the IMU orientation in a non-flat plane. The yaw angle is given by a magnetometer. Typical magnetometers allow us to keep the sensor reasonably small (*i.e.* smaller than the width of a finger), but come with trade off between size and accuracy. They are suited for movements that have low accelerations, but this was not the case in our study. They are also prone to interferences – such as those cause by the tablet and screen hardware (*i.e.* soft iron effects). Both pitch and roll angles are therefore determined using only the accelerometer and gyroscope data along with the implementation version of Madgwick’s IMU and AHRS algorithms designed for invalid magnetometer measurements [17].

We considered and tested other solutions using an *OptiTrack* motion capture system with 4 *Prime 13* cameras tracking the position and orientation of a tablet laid flat on a desk and one finger of the participant (Figure 3a). Reflective markers were attached to the tablet. One solution was to attach reflective markers onto the skin. However, vision-based systems such as this are not suitable due to frequent occlusion by the hand and infra red reflections due to the screen glass. A second approach was to shift the markers using a long 3D printed rigid skeleton (figure 3b) extending the orientation of the first phalanx as used in [1]. The rigid body weighed 4 g and had three rods of different lengths: long (95 mm), medium (40 mm) and short (35 mm) (Figure 3c). It was attached such that the *long* rod was aligned with the first phalanx and the *short* rod was orthogonal to the plane defined by the fingernail. Even though lightweight minimizing tracking occlusion problems and designed to be as unobtrusive as possible, we could not ensure natural finger orientations. The choice of the IMU was therefore the best compromise: it gives us reliable absolute

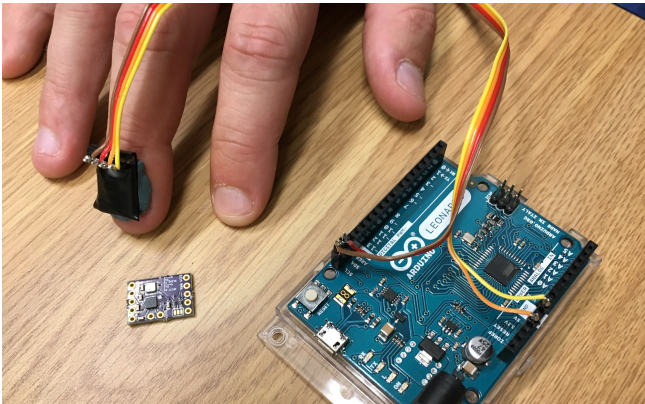


Figure 2: IMU and Arduino Leonardo board used in the experiment. The IMU was fixed on top of the first phalanx of a finger using *Blu Tack*.

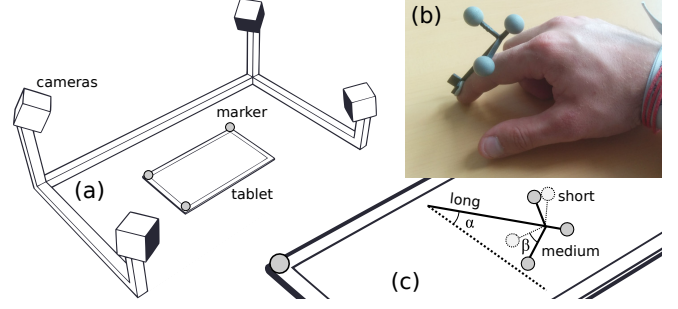


Figure 3: Motion capture solution using a rigid body attached to the fingernail: (a) tablet laid flat with 4 camera motion tracking system to track its position and orientation; (b) finger orientation was tracked using a rigid body attached to the fingernail; (c) pitch angle α is the angle between the long rod of the rigid body and the tablet plane, the roll angle β is defined using the medium rod.

pitch and roll orientation but is constrained to the use of a flat tablet.

Setup evaluation

Prior to our experiment, we conducted an evaluation where we placed the IMU at known orientations using a laser-cut wood frame. For a given pitch/roll posture, we measured the orientation provided by our sensor (taking 50 samples). In between each measurement of the controlled static poses, the sensor was moved and rotated quickly away and set back to the evaluated posture. As soon as the sensor was set back, a measurement was triggered. The overall accuracy⁴ was -1.0° for pitch and -1.5° for roll. The overall precision⁵ was 5.3° for pitch and 8.7° for roll. Table 1 shows the different precision and accuracy for the tested postures.

Tasks

Participants performed a sequence of tasks using our custom tablet application. The tasks simulated common touch interactions. In total 63 TASKS were tested. The different tasks were:

- Tap (figure 4b): pressing a circular target on the screen. 15 locations each centred on the nodes of a 5 rows by 3 column grid were tested. All the targets had the same comfortable size of 1.5cm diameter.

⁴Distance between the mean angle and the target angle.

⁵Four times the standard deviation.

Pitch tested	Roll tested	Pitch precision	Pitch accuracy	Roll precision	Roll accuracy
0°	0°	1.7°	-0.3°	0.7°	-0.1°
0°	45°	3.1°	-0.3°	2.7°	-0.9°
0°	90°	1.7°	-0.4°	2.1°	0.2°
45°	0°	0.9°	-1.1°	1.4°	-6.0°
45°	45°	3.6°	-3.6°	1.7°	-2.1°
90°	0°	1.6°	-0.2°	0.8°	-0.3°
all	all	5.3°	-1.0°	8.7°	-1.5°

Table 1: Summary of the accuracies and precisions achieved by our setup for know pitch and roll orientations.

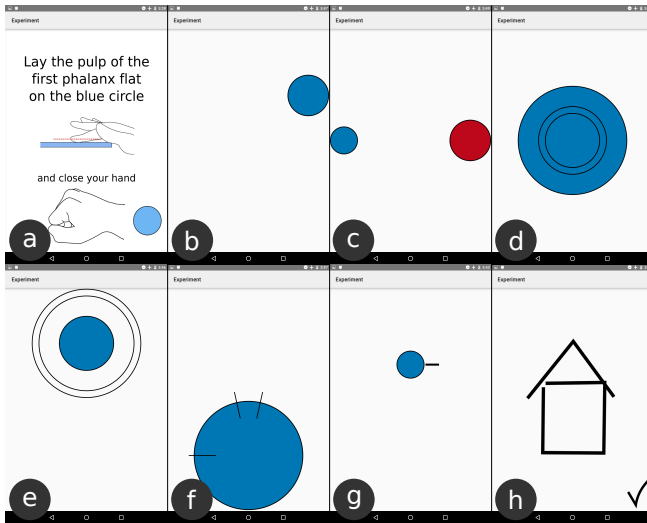


Figure 4: Different tasks explored: (a) calibration screen; (b) tap task; (c) drag task; (d) scale-down task; (e) scale-up task; (f) rotation task; (g) flick task; (h) trace task.

- Drag (figure 4c): moving a circular object inside a circular target area. 6 horizontal directions (from left to right and reverse, located at the top, middle and bottom part of the screen) and 6 vertical directions (from top to bottom and reverse, located at the left, middle and right part of the screen) were tested. All the circular objects and target areas had the same sizes of 1.6cm and 2.3cm diameter.
- Scale (figure 4d-e): resizing a circular object until its edge fits into a ring-shaped object. 3 scales up and 3 scales down were tested, varying only the centre position of the object (top, middle, bottom). The maximum size of the circular object was 6.3cm diameter and the minimum size was 3.1cm diameter. The ring object had a width of .4cm.
- Rotation (figure 4f): rotating a circular object until a black mark fits between a defined aperture on the top edge of the circular object. 3 clockwise and 3 counter clockwise 90-degrees rotation were tested, varying only the centre position of the object (top, middle, bottom). The angle of the aperture was 25 degrees.
- Flick (figure 4g): performing a flick gesture on a circular object. 12 flick gestures were tested: 3 starting positions of the circular object (top, middle, bottom) for each cardinal direction. The circular objects had the same comfortable size of 1.6cm diameter.
- Trace (figure 4h): following a multi stroke path. 12 paths were tested: 4 different types of path (a smiley face, a house, a pig tail and a cross) centred on 3 starting position (top, middle, bottom).

Comfortable target sizes were determined according to the literature [11, 30, 35].

Procedure and design

The experimenter started by explaining the different tasks that were to be encountered during the experiment. Participants

were instructed to use the selected finger for all tasks. For tasks that required two fingers, participants were free to use any other finger from the same hand. In order to observe natural orientations, we did not impose any constraint on the fingers' orientations. Participants were then showed the calibration procedure which consisted in laying the first phalanx of the imposed finger flat on a circular target and then closing the fist (figure 4a). The circular targets appeared on the left side of the screen for the left hand (close to the top left corner, middle of the left bezel or close to the bottom left corner) and on the right part of the screen for the right hand⁶. Participants completed each of the 63 tasks using all ten fingers. In between each task (tap and drag tasks were grouped into threes), a calibration procedure was displayed, to prevent errors from Blu Tack repositioning.

Half of the participants started with the 5 fingers of the left hand, the other half started with the fingers of the right hand. The presentation order of FINGER (thumb, index, middle, ring, little) was randomized for each hand of each participant, and the order of TASK was also randomized. Tasks which were not completed in a single movement were continued by the participant and simply resulted in more data to analyse.

Participants remained seated during the whole experiment and could take a break at any time. Performing the set of tasks took approximately 3 to 5 minutes per finger. The whole experiment lasted 45 minutes on average.

During the experiment participants were asked to report to the experimenter if the sensor was getting loose or if it interfered with their interaction. On average, this happened at most 1 or 2 times per participant. No participants reported any discomfort during the study, but a few commented that they were not used to interacting with certain fingers (such as the non-dominant-hand little finger).

Participants

We recruited 12 volunteers (mean age 27, SD 4.6, 1 female, 1 left-handed). All were daily users of multi-touch devices. Participants received an honorarium of \$10.

RESULTS

In this section we describe the pitch and roll distributions of the different fingers for all the tasks performed in the experiment. In total we gathered 449,890 data points. Each of those data points corresponds to a touch frame. As the touch input frequency is variable, we first normalized the data using a 50 ms period re-sampling. Given the intentional lack of instructions regarding speed, similar gestures were performed at different paces resulting in over-representation of slow movements. We therefore binned, using the mean, the re-sampled data points of all the separated touch movements, into quartiles corresponding to the quartile of the total duration of touch lifespan. After re-sampling and binning into

⁶Since finger morphology differs between fingers and participants, the purpose of the calibration procedure is to log the absolute pitch and roll angles of the flat phalanx which are used later to compute the actual orientation of the finger. Closing the fist avoids possible positioning bias and forces participants to use their finger naturally. Varying the position further reduces the possibility of bias.

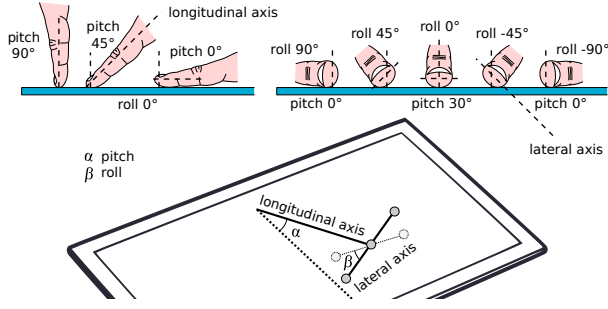


Figure 5: Definition used for the pitch and roll angles.

quartiles, 4 QUARTILES \times 63 TASKS \times 10 FINGERS = 2,520 data points per participant were used for the statistics. Figure 6 however represents the 50ms re-sampled data points.

All quantitative analyses are repeated measures MANOVA on both pitch and roll angles as dependent variables, using the *manova* command of *R* and summarized using the Pillai-Bartlett trace. We chose MANOVAs for their robustness to the eventual lack of independence between samples (this problem can arise in the QUARTILES comparisons), as well as the fact that a violation of the multivariate normality assumption has typically little effect on the p-values [14, p138]. Furthermore, we used the Pillai-Bartlett trace which is the most conservative test and is also the most robust in cases of violation of the assumptions, at least for balanced models. Pairwise comparisons using t tests with Holm adjustment method are then used when significant effects are found on each dependent variable separately. The different factors we use in our analysis are: FINGERS and QUARTILES. The latter corresponds to the different quartile of a touch lifespan: 25% corresponds to the first quartile, 50% the second quartile, 75% the third and 100% the last one.

In the different figures and tables, *T* stands for *Tap*, *D* for *Drag*, *S* for *Scale*, *S_d* for *Scale-Down*, *S_u* for *Scale-Up*, *R* for *Rotation*, *R_{cc}* for *Counter-Clockwise Rotation*, *R_c* for *Clockwise Rotation*, *F* for *Flick*, *F_s* for *Flick towards south*, *F_n* for *Flick towards north*, *F_e* for *Flick towards east*, *F_w* for *Flick towards west*, *Tr* for *Trace*, *LL*, *LR*, *LM*, *LI* and *LT* represent the finger of the left hand (from little to thumb) and *RT*, *RI*, *RM*, *RR* and *RL* the finger of the right hand.

Angle definition

In the remainder of the paper, the pitch angle corresponds to the angle between the plane defined by the screen and the vector defined by the longitudinal axis of the finger (*e.g.* axis following the bone of the first phalanx). The roll is defined as 0° when the lateral axis of the finger (*e.g.* axis traversing sideways to the first phalanx) is parallel to the tablet plane. Figure 5 illustrates the different angles and axes described.

Calibration

We found no effect of calibration position (all $F < 0.92$; all $p > 0.44$) nor interaction between calibration position and finger (all $F < 0.73$; all $p > 0.87$) for the different tasks. This result suggests that the calibration procedure did not affect the orientations used by the participants during the experiment.

Tasks	finger	Min mean	95% CI	finger	Max mean	95% CI
T	LL	23°	[20°; 26°]	RT	31°	[28°; 34°]
D	RL	24°	[20°; 27°]	RT	37°	[34°; 41°]
S	LT	16°	[10°; 22°]	RI	42°	[38°; 47°]
<i>S_d</i>	LT	14°	[9°; 19°]	RM	42°	[36°; 49°]
<i>S_u</i>	LT	16°	[9°; 23°]	RI	42°	[37°; 47°]
R	LT	23°	[17°; 29°]	RM	50°	[44°; 56°]
<i>R_{cc}</i>	LT	17°	[12°; 22°]	LM	48°	[42°; 54°]
<i>R_c</i>	RT	23°	[18°; 29°]	RM	57°	[49°; 65°]
F	LL	25°	[22°; 27°]	RT	37°	[34°; 40°]
<i>F_s</i>	RL	32°	[29°; 36°]	LM	42°	[38°; 45°]
<i>F_n</i>	LL	24°	[20°; 28°]	RM	33°	[28°; 38°]
<i>F_e</i>	LL	19°	[16°; 22°]	RT	41°	[37°; 46°]
<i>F_w</i>	RL	21°	[17°; 25°]	LM	36°	[32°; 41°]
Tr	LL	23°	[21°; 25°]	RT	39°	[36°; 42°]

Table 2: Summary of the minimum and maximum mean pitch angle and corresponding 95% CI, for each task. Fingers for which minimum and maximum values were achieved are indicated.

Pitch and roll distributions

Figure 6 shows the distributions of the pitch and roll angles for all the data points gathered for each finger and each task. In table 3, we summarize the results of the statistical tests performed for each task on pitch and roll as dependent variables and FINGERS and QUARTILE as factors.

We found a significant main effect of FINGER for the different tasks. Post-hoc tests reveal numerous significant differences between fingers for roll (table 5) and pitch (table 6). The differences seem to be mainly due to the roll angle. Table 2 summarizes the minimum and maximum mean pitch angles, as well as the 95% confidence interval, for each task and for which finger those were achieved. We also report the equivalent for the roll angle in table 4. Thumbs are without surprise the fingers with the most extreme means. According to figure 6 and table 5, within each hand, the little, ring and middle fingers are mostly similar, the index finger is similar to the middle finger and the thumb is apart (except for the right thumb and little finger). The differences between fingers according to the pitch variables are less marked. Those differences mostly come from actions inducing a high range of motion like rotations or scalings.

These different behaviours can be explained by hand morphology. The index finger is more dexterous and is often used with a closed-hand “pointing” pose, enabling a range of motion roll centered on the table surface with little interference from other fingers. The middle, ring and little finger have less dexterity and are typically used with an open hand making it hard to interact with the side part of the finger facing the thumb without having other fingers interfere with erroneous tablet contacts. It results in a slight roll shift in the distributions (toward negative roll values for the left hand and positive roll values for the right hand). Since the thumb is opposable to the other fingers, there is a symmetrical problem, resulting in a symmetrical distribution (with the roll values shifted toward positive values for the left hand and negative values for the right hand).

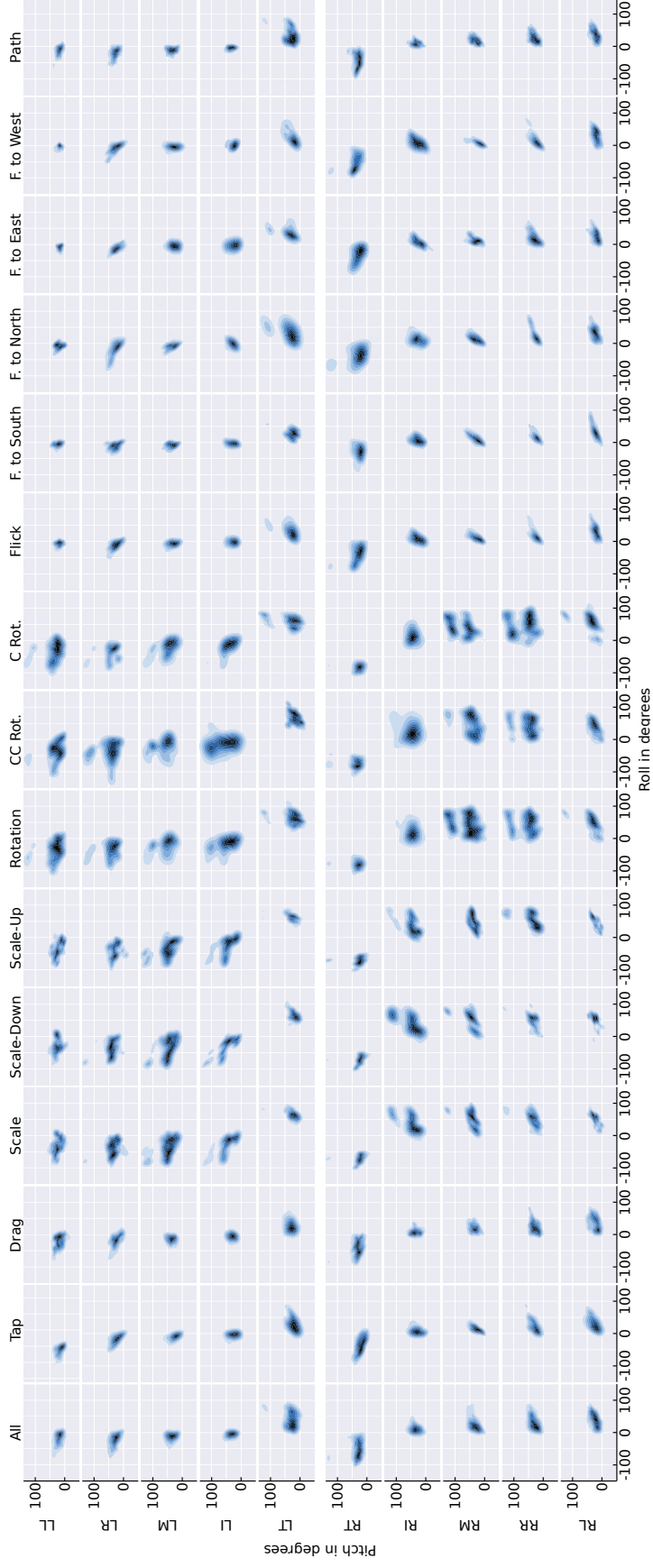


Figure 6: Distribution of first phalanx pitch and roll angles of the 10 fingers. Each row correspond to one finger. The columns represent the different tasks of the experiment. The first column (i.e. *All*) represents the pitch/roll distributions across all tasks. The lightest green represents 90% of the observations with subsequent levels of darker greens decreasing density by 10%.

		Tap	Drag	Scale	S. Down	S. Up	Rotation	R. CCw	R. Cw	Flick	Flick _{South}	Flick _{North}	Flick _{East}	Flick _{West}	Trace
Finger	F	7.1	23.1	32.6	26.9	32.6	28.2	21.7	23.2	14.6	10.4	10.3	9.4	12.3	21.8
	Pillai Λ	0.36	0.67	0.84	0.74	0.83	0.77	0.65	0.68	0.49	0.37	0.37	0.35	0.43	0.65
	p	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Quartile	F	0.0	0.4	0.0	0.2	0.1	0.5	0.3	0.8	0.3	9.7	1.0	0.5	0.0	0.1
	Pillai Λ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
	p	0.96	0.69	0.96	0.81	0.94	0.62	0.72	0.44	0.74	<0.01	0.38	0.63	0.96	0.90
F×Q	F	1.4	2.3	1.1	1.2	1.9	1.6	1.6	2.3	1.8	1.7	2.5	1.8	1.9	2.3
	Pillai Λ	0.08	0.10	0.05	0.05	0.08	0.07	0.07	0.10	0.07	0.07	0.10	0.08	0.08	0.10
	p	0.11	<0.01	0.31	0.28	0.01	0.06	0.05	<0.01	0.03	0.04	<0.01	0.02	0.01	<0.01

Table 3: Summary of the MANOVAs analysis on the pitch and roll dependent variables for the FINGERS and QUARTILES factors for each tasks. Significant effects are reported in bold.

Tasks	finger	Min mean	95% CI	finger	Max mean	95% CI
T	RT	-33°	[-38°; -28°]	LT	37°	[33°; 40°]
D	RT	-36°	[-40°; -32°]	LT	39°	[36°; 42°]
S	RT	-66°	[-69°; -62°]	LT	68°	[65°; 71°]
S_d	RT	-67°	[-71°; -63°]	LT	70°	[67°; 73°]
S_u	RT	-65°	[-69°; -61°]	LT	67°	[63°; 70°]
R	RT	-71°	[-74°; -67°]	LT	71°	[68°; 74°]
R_{cc}	RT	-68°	[-73°; -62°]	LT	77°	[73°; 80°]
R_{cc}	RT	-73°	[-78°; -68°]	LT	67°	[64°; 71°]
F	RT	-36°	[-41°; -32°]	LT	40°	[37°; 44°]
F_s	RT	-27°	[-32°; -21°]	LT	35°	[30°; 39°]
F_n	RT	-36°	[-42°; -31°]	LT	43°	[39°; 47°]
F_e	RT	-33°	[-40°; -27°]	LT	46°	[42°; 50°]
F_w	RT	-44°	[-49°; -39°]	LT	39°	[33°; 44°]
Tr	RT	-35°	[-39°; -31°]	LT	43°	[39°; 47°]

Table 4: Summary of the minimum and maximum mean roll angle and corresponding 95% CI, for each task. Fingers for which minimum and maximum values were achieved are indicated.

Time distributions

We found no significant effect of QUARTILES (second row of table 6). However we found significant interactions between FINGERS and QUARTILES for some of the tasks (third row of table 6). Post-hoc analysis focused on each finger (with no adjustment method) revealed differences between: the first and third quartile on roll for the left thumb for the counter-clockwise rotation task ($p < 0.04$); the last quartile and all the others on roll for the left ring (all $p < 0.04$), the left middle (all $p < 0.01$) and the left index finger (all $p < 0.02$) for the flick toward South task; and the first and last quartile on roll for the right thumb for the flick toward East task ($p < 0.04$). Those results suggest a certain consistency within a single touch in the pitch/roll orientation while interacting. However, given our experimental design, it could also be due to the short nature of the touch lifespans.

Task distributions

We ran similar analysis, for each finger with TASKS and QUARTILES as factors.

We found a significant main effects of TASK for all the different fingers (all $F > 3.4$; all $p < 0.01$). After gathering post-hoc tests for pitch and roll (see table 7) analysis revealed that tapping, dragging and flicking distributions are similar for most of the fingers and significantly different from both scaling and rotation distributions. Scaling and rotation distributions are also significantly different for the majority of fingers. We found no effect of QUARTILE nor interactions between TASK and QUARTILE (all $F < 1.5$; all $p > 0.22$). Those results suggest that finger orientations differ in function of the number of fingers interacting at the same time.

FOLLOW UP EXPERIMENT

In order to test the influence of the tablet orientation, we conducted a follow-up study using the same apparatus and procedure as the main experiment. In this study, we tested two tablet orientations: tilted at 15° and tilted at 30°. For each conditions, we ran 8 new volunteers (15°: mean age 25.8, SD 5.4, 3 females, 2 left-handed; 30°: mean age 27.6, SD 9, 4

females, 1 left-handed). All participants were also daily users of multi-touch devices as in the first experiment.

In the following, we analyse the pitch and roll angles in the world frame of reference. We used the same statistical methods as the previous experiment. All quantitative analyses are repeated measures MANOVA on both pitch and roll angles as dependent variables summarized using the Pillai trace. Pair-wise comparisons using t tests with Holm adjustment method are then used when significant effects are found on each dependent variables separately. We tested ORIENTATIONS, corresponding to the different tilts of the tablet, as a between subject factor.

Influence of tablet orientation

For each pair of task and finger, we found a significant main effect of ORIENTATION on both pitch and roll dependent variables (all $F > 6.2$; all Pillai $\Lambda > 0.22$; all $p < 0.01$). Post-hoc analysis revealed differences between all orientations for each pair of task and finger (all $p < 0.05$) except between tilt 15° and 30° for the right thumb during rotations tasks including clockwise and counter-clockwise rotations alone (all $p > 0.17$). This result suggests that participants adapted their finger orientation as a function of the tablet tilt. One could hypothesize that we use similar finger orientations in the screen frame of reference to those used when interacting with a flat tablet. If so, the previous descriptions of finger orientations on flat screen as well as their derived design insights could still stand. However, further experiments are necessary to confirm or reject this hypothesis.

Range of orientations

We also looked at the bounding boxes (length of the pitch and roll ranges in the world frame of reference) of the distribution to assess if there are differences in terms of range of orientations. The results generally follow the same trend: for the vast majority of pairs task \times finger, except while tapping, flicking South, East and West, the change in the tablet tilt has a significant impact on the range of orientation. Post-hoc tests and analysis of the mean bounding box (table 8) revealed the following trend: when there are differences, it appears that the more the tablet is tilted, the smaller the range of orientation used (except for the right thumb during scaling tasks). The latter observation would suggest that (except while tapping, flicking South, East and West) participants used more consistent finger orientations when the tablet was pitched at 15° and 30° compared to the tablet laid flat. In these cases, the range of orientations described in the flat tablet conditions are different. However, one can hypothesize that the greater consistency of finger orientations can be centred around the mean orientation of the flat tablet distributions. If so, some design insights (e.g. using high pitch as a secondary touch input) could still stand. Again, further analysis are needed to test those hypotheses.

DISCUSSION

Using figure 6 and table 2, we can observe that the orientations used while interacting are relatively low pitched on average. Following Mayer *et al.* design guidelines [21], high pitched values can be comfortably used to enable secondary

	LL	LR	LM	LI	LT	RT	RI	RM	RR
LL	-	-	-	-	-	-	-	-	-
LR	-	-	-	-	-	-	-	-	-
LM	R_{all}, Tr	R_{all}, F, F_n, Tr	-	-	-	-	-	-	-
LI	$D, R, R_{cc}, F, F_e, F_w, Tr$	all but T, S, S_d	D	-	-	-	-	-	-
LT	all tasks	all tasks	all tasks	all tasks	-	-	-	-	-
RT	all tasks	all tasks	all tasks	all tasks	all tasks	-	-	-	-
RI	all tasks	all tasks	all but F_w	all but F_e, F_w	all tasks	all tasks	-	-	-
RM	all tasks	all tasks	all tasks	all but F_w	all but F_n	all tasks	D, R, F, F_w, Tr	-	-
RR	all tasks	all tasks	all tasks	all tasks	all but T, S_u, R_c, F_s, F_n	all tasks	all but T, S_d, R_{cc}	-	-
RL	all tasks	all tasks	all tasks	all tasks	S_d, R, R_{cc}, F_e	all tasks	all but R_{cc}	all but S_{all}, R, R_{cc}	T, D, F, F_s, Tr

Table 5: Summary of the post-hoc analysis on Roll for the FINGER factor. The cell of the table indicates the tasks on which two fingers (first row and first column) differ. All $p < 0.05$.

	LL	LR	LM	LI	LT	RT	RI	RM	RR
LL	-	-	-	-	-	-	-	-	-
LR	$D, S_d, R, R_{cc}, F, F_e, Tr$	-	-	-	-	-	-	-	-
LM	all but T, R_c, F_e	D, S, S_u	-	-	-	-	-	-	-
LI	D, S_{all}, Tr	S, S_u	D, F_n	-	-	-	-	-	-
LT	D, F, F_e, F_w, Tr	S_d, R, R_{cc}	$D, S_{all}, R, R_{cc}, F_n$	S_{all}, R_{cc}, F_e	-	-	-	-	-
RT	D, F, F_e, F_w, Tr	S_d, R, R_c, F_w	$S_{all}, R, R_c, F_n, F_e$	S_{all}, F_e, F_w	R_{cc}	-	-	-	-
RI	T, D, S_{all}, F_e, Tr	D, S, S_u	R	D, S_{all}, R_{cc}	S_{all}	S_{all}	-	-	-
RM	all but T, R_{cc}	D, R_c	R_c	D, R, R_c, F_e	D, S, S_d, R_{all}, F_n	S, S_d, R, R_c, F_n	R, R_c	-	-
RR	all but S_d, R_{cc}, F_s, F_n	D	D	S_d, F_e	S_{all}, R_{all}	S_{all}, R, R_c	R_c	D	-
RL	T, F_e	S, S_d, R, R_{cc}	$D, S_{all}, R, R_{cc}, Tr$	T, S_{all}, Tr	Tr	D, F_w	D, S_{all}	D, S_{all}, R, R_c	S_{all}, R, R_c

Table 6: Summary of the post-hoc analysis on Pitch for the FINGER factor. The cell of the table indicates the tasks on which two fingers (first row and first column) differ. All $p < 0.05$.

	T	D	S	R	F
T	-	-	-	-	-
D	RT, LL	-	-	-	-
S	all fingers	all fingers	-	-	-
R	all fingers	all fingers	all but LI, LT, RI	-	-
F	RT	LL	all fingers	all fingers	-
Tr	LI, RT, LL		all fingers	all fingers	

Table 7: Summary of the post-hoc analysis on Roll and Pitch for the TASK factor. The cell of the table indicates the fingers on which two tasks (first row and first column) differ. All $p < 0.04$.

actions without disturbing natural finger orientation during the primary task. Studying Figure 6, we can also observe that the index and middle fingers from both hands are not used with excessive roll angles – except for rotations and scalings – (left: mean roll angle of -4° with 95% CI $[-8^\circ; -3^\circ]$; right: mean roll angle of 12° with 95% CI $[9^\circ; 15^\circ]$). Absolute high roll angles could also be used as another degree of freedom.

Another possible use of angle characterization could help filtering out unwanted contacts. If only contacts starting within the normal range of orientations are processed, it could reduce unintentional interaction with devices that could be due to external factors such as touchscreen repositioning.

In recent years finger identification have been explored to enrich touch expressiveness. Arguably, the most convenient technology to enable it is to recognize fingerprints. Using capacitive fingerprint scanner one can envision an entire capacitive display able to read fingerprints. Sonavation⁷ has

⁷<http://www.sonavation.com/touch-under-glass/>

	LL	LR	LM	LI	LT	RT	RI	RM	RR	RL
T	ooo	ooo	ooo	ooo	ooo	ooo	ooo	ooo	ooo	ooo
D	o▲	▼▼	▼▼	▼▼	▼▼	o▲	▼▼	▼▼	▼▼	▼▼
S	▼▼	▼▼	▼▼	▼▼	ooo	ooo	ooo	▼▼	▼▼	▼▼
S_d	▼▼	ooo	▼▼	▼▼	ooo	o▲	▼▼	▼▼	▼▼	▼▲
S_u	ooo	▼▼	▼▼	▼▼	ooo	o▲	▼▼	▼▼	▼▼	▼▼
R	▼▼	▼▼	▼▼	▼▼	▼▼	▼▲	▼▼	▼▼	▼▼	▼▼
R_{cc}	▼▼	▼▼	▼▼	▼▼	ooo	ooo	ooo	▼▼	▼▼	▼▼
R_c	▼▼	ooo	ooo	▼▼	ooo	▼▼	▼▼	▼▼	▼▼	▼▼
F	ooo	ooo	o▼	o▼	ooo	▼▼	▼▼	ooo	ooo	▼▼
F_s	ooo	ooo	o▼	ooo	ooo	ooo	ooo	ooo	ooo	▼▼
F_n	▼▼	ooo	ooo	ooo	▼▼	▼▼	▼▼	▼▼	ooo	▼▼
F_e	ooo	ooo	ooo	ooo	ooo	ooo	ooo	ooo	ooo	ooo
F_w	ooo	ooo	ooo	ooo	ooo	▼▼	ooo	ooo	ooo	ooo
Tr	▼▲	ooo	▼▼	▼▲	ooo	▲oo	o▲	▼▼	▼▼	▼▼

Table 8: Summary of the post-hoc on Roll and Pitch in the world frame of reference for the different tilt of tablet. ooo correspond to the comparison between tilt 0° and 15° , 0° and 30° , and 15° and 30° . When o is replaced by ▲ the second tilt yields a bigger area of bounding box, when replaced by ▼ the second tilt yields a smaller area. For instance, o▲▼ means that the 30° bounding box is bigger than the 0° one and that the 30° bounding box is smaller than the 15° one. All $p > 0.05$.

patented a touch sensor [31] capable of detecting touch and biometric information such as fingerprints under a glass layer. The best case scenario for fingerprint recognition is when the finger contacts the sensor flat since it is well known this area of the skin carries enough information in *minutiae* to discriminate individuals and fingers [19]. However it is unclear if non-flat fingers also have enough minutiae to reliably identify them. Using our characterization, we are able to identify which partial part of the fingerprint (*i.e.* which finger orientation) has to be recognizable in order for such a technology

to support finger identification in a normal context of use. It seems that from our findings, the side of the finger pad is the key part that has to be recognizable.

Another takeaway from this study is the difference between the thumb roll orientations and those from the other fingers of the same hand. Orientation seems to be a good discriminating information to identify the thumb from the rest of the fingers. Furthermore, unsurprisingly the physical symmetry of our hand is preserved relatively well when interacting. A GUI aware of the roll angle at which fingers interact with it could be used to adapt itself automatically to handedness (for instance, by adapting the position of contextual menus in a table top interaction context). However, differentiating the left hand from the right hand seems only possible if a subset of finger are used: either all fingers but thumbs or just the thumbs.

LIMITATIONS AND FUTURE WORK

This work characterizes the pitch and roll orientations for all fingers for a flat touchscreen and can be useful for several contexts of interaction (e.g. horizontal tabletops or the use of tablets flat on a desk). However the lack of yaw information reduced the number of factors that could be tested. As measuring natural yaw, pitch and roll finger orientations together remains an open problem, this paper provides only a starting point for the area. An obvious direction for future works is to identify a robust technical solution to measure yaw, pitch, and roll, in a way that does not interfere with the user's natural behaviour. Combining an IMU with the use of state-of-the-art yaw recognition (e.g. [37]) is worth investigating, since it is not clear to what extent finger postures are constrained. Our results can provide a baseline for new techniques which seek to measure natural orientations using more cumbersome settings. Nevertheless, our cheap (less than \$60) and easily reproducible setup can be used to investigate other tasks (e.g. typing on a double-touchscreen laptop) or input factors (e.g. position of the screen, such as flat on the lap as identified by [15]).

CONCLUSION

The performance characteristics of atomic touch interactions, such as tap, drag, scale, rotation and flick, have been extensively studied. However, less is known regarding how they are carried out by users. In this paper we studied the natural pitch and roll orientation of all ten fingers while performing such actions. We used an IMU in a low cost and easily reproducible setup to accurately measure finger orientation. Our results provide a set of baselines about pitch and roll orientation for all the fingers of both hands for one setting (a flat tablet in front of the user). We found that for a given hand, the little, ring and middle fingers are used in a similar manner, whereas the thumb uses different range of orientations. Additional analyses about how changing the angle of the tablet affects people's finger orientations suggest that ranges of orientation tighten as the tablet pitch increases. Our data provides designers and researchers with a new resource to better understand the use of pitch and roll as new degrees of freedom (e.g. using finger pitch as a secondary mode) and to

determine whether new sensing techniques are feasible (e.g. using fingerprints for identifying specific finger touches).

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